arXiv:hep-ph/9908259v1 4 Aug 1999

Drell-Yan and J/ψ production in high energy proton-nucleus and nucleus-nucleus collisions*

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The distributions of outgoing protons and charged hadrons in high energy proton-nucleus collisions are described rather well by a linear extrapolation from proton-proton collisions. This linear extrapolation is applied to precisely measured Drell-Yan cross sections for 800 GeV protons incident on a variety of nuclear targets. The deviation from linear scaling in the atomic number A can be accounted for by energy degradation of the proton as it passes through the nucleus if account is taken of the time delay of particle production due to quantum coherence. We infer an average proper coherence time of 0.4±0.1 fm/c. Then we apply the linear extrapolation to measured J/ψ production cross sections for 200 and 450 GeV/c protons incident on a variety of nuclear targets. Our analysis takes into account energy loss of the beam proton, the time delay of particle production due to quantum coherence, and absorption of the J/ψ on nucleons. The best representation is obtained for a coherence time of 0.5 fm/c, which is consistent with Drell-Yan production, and an absorption cross section of 3.6 mb, which is consistent with the value deduced from photoproduction of the J/ψ on nuclear targets. Finally, we compare to recent J/ψ data from S+U and Pb+Pb collisions at the SPS. The former are reproduced reasonably well with no new parameters, but not the latter.

1. INTRODUCTION

There are two extreme limits of a projectile scattering from a nucleus. When the cross section of the projectile with a nucleon is very small, as is the case for neutrinos, Glauber theory says that the cross section with a nuclear target of atomic number A grows linearly with A. When the cross section with an individual nucleon is very large, as is the case for pions near the delta resonance peak, the nucleus appears black and the cross section grows like $A^{2/3}$. A more interesting case is the production of lepton pairs with large invariant mass, often referred to as Drell-Yan, in proton-nucleus collisions. Both

*Presented by J. Kapusta and C. Gale.

the elastic and inelastic cross sections for proton-nucleon scattering are relatively large, but the partial cross section to produce a high mass lepton pair, being electromagnetic in origin, is relatively small. Experiments have shown that the inclusive Drell-Yan cross section grows with A to a power very close to 1. The theoretical interpretation is that the hard particles, the high invariant mass lepton pairs, appear first and the soft particles, the typical mesons, appear later due to quantum-mechanical interference, essentially the uncertainty principle. These quantum coherence requirements also lead to the Landau-Pomeranchuk-Migdal effect [1]. Deviations from the power 1 by high precision Drell-Yan experiments [2] at Fermi National Accelerator Laboratory (FNAL) suggest that it may be possible to infer a finite numerical value for the coherence time. That is one of our goals.

Another of our goals is to take this coherence time effect into account when extracting an absorption cross section for J/ψ on nucleons for J/ψ particles produced in high energy proton-nucleus collisions. After extracting this absorption cross section, we use it to carry out parameter-free calculations of J/ψ production in S+U and Pb+Pb collisions to help us ascertain the likelihood that new physics must be invoked, that is, quark-gluon plasma.

Before addressing these goals it is imperative to have a basic description of high energy proton-nucleus collisions which reproduces the essential data on outgoing baryons and mesons. We will use one particular theoretical approach, referred to as LEXUS. Using input from nucleon-nucleon collisions together with geometry, LEXUS does describe the data very well. See [3–5]. However, it important to realize that any model or extrapolation which incorporates the same basic features will lead to the same conclusions we find here.

2. PROTON-NUCLEUS COLLISIONS

2.1. Drell-Yan production

Consider a description of the Drell-Yan process in a proton-nucleus collision. One limit is full energy degradation of the proton as it traverses the nucleus. Produced hadrons appear immediately with zero coherence time, causing the proton to have less energy available to produce a Drell-Yan pair at the backside of the nucleus. The other limit is usually referred to as Glauber, although this is a bit of a misnomer. Produced hadrons, being soft on the average, do not appear until after the hardest particles, the Drell-Yan pair, have already appeared. This is the limit of a very large coherence time, and it allows the proton to produce the Drell-Yan pair anywhere along its path with the full incident beam energy. An intermediate case is one of finite, nonzero coherence time. By the time the proton wants to make a Drell-Yan pair on the backside of the nucleus, hadrons have already appeared from the first collision but not from the second. Therefore the proton has more energy available to produce the Drell-Yan pair than full zero coherence time but less energy than with infinite coherence time. This ought to result in an A dependence less than 1, with the numerical value determined by the coherence time. It is instructive to contemplate the relative importance of energy loss and coherence time for an 800 GeV proton incident on a *very* large nucleus, such as a neutron star: Can one imagine the proton reaching the backside of a neutron star and producing a Drell-Yan pair without having suffered *any* energy loss?

Consistent with our philosophy to describe everything in terms of hadronic variables we

should use a parametrization of measured Drell-Yan cross sections in pp and pn collisions. However, we need these over a very broad energy range because of the decreasing energy of the proton as it cascades through the nucleus, and such broad measurements have not been made. Therefore, we compute the Drell-Yan yields in individual pp and pn collisions using the parton model with the GRV structure functions [6] to leading order with a K factor. These structure functions distinguish between pp and pn collisions. We have compared the results to pp collisions at the same beam energy of 800 GeV [7] and found the agreement to be excellent for all values of x_F.

The experiment E772 [2] measured the ratio $\sigma_{pA}^{\rm DY}/(\sigma_{pd}^{\rm DY}/2)$. Were there no energy loss and all nuclei were charge symmetric this ratio would be equal to A. The experiment measured muon pairs with invariant mass M between 4 and 9 GeV and greater than 11 GeV to eliminate the J/ψ and Υ contributions. The data has been presented in 7 bins of Feynman x_F from 0.05 to 0.65. (Recall that x_F is the ratio of the muon pair longitudinal momentum to the incident beam momentum in the nucleon-nucleon c.m. frame.) Data for an exemplary value of x_F is shown in Figure 1. The data should fall on the dashed line

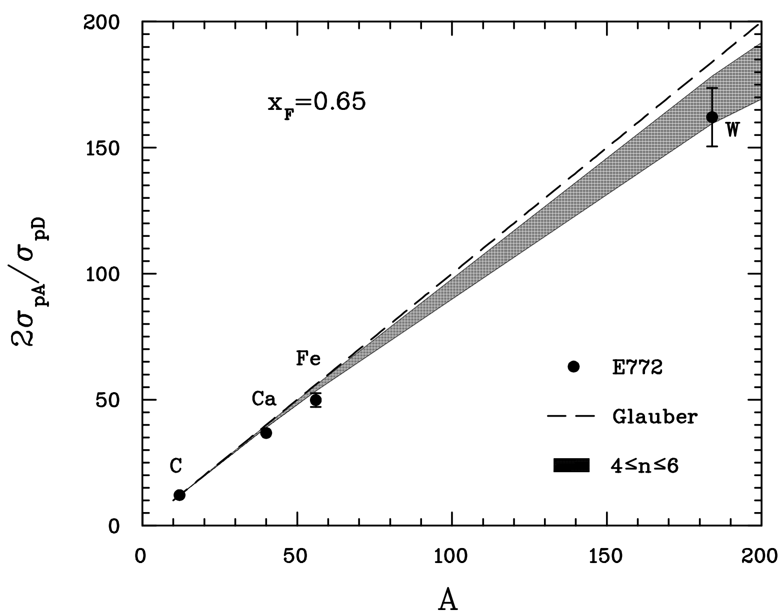

Figure 1. The ratio of the pA Drell-Yan cross section to the proton-deuterium cross section divided by 2 for a beam energy of 800 GeV. The data are from E772 [2]. The dashed line assumes a scaling linear in the atomic number A. The shaded region represents our calculations with a coherence time ranging from 4 to 6 proton-nucleon collisions, both elastic and inelastic. We computed with target nuclei C, Ca, Fe, W and Pb and interpolate between with straight lines to guide the eye. The value of Feynman x_F of the Drell-Yan pair is 0.65.

if the ratio of cross sections is A. There is a small but noticeable departure for tungsten and at the largest value of x_F. This is to be expected if energy loss plays a role as it must

affect the largest target nucleus and the highest energy muon pairs the most [8].

We have computed the individual cross sections $\sigma_{pA}^{\rm DY}$ with a variable time delay. The proton cascades through the nucleus as described earlier, but we assume that the energy available to produce a Drell-Yan pair is that which the proton has after n previous collisions. Thus $n = 0$ is full energy loss and $n = \infty$ is zero energy loss. We have taken the resulting proton-nucleus Drell-Yan cross section, multiplied it by 2, divided it by the sum of the computed pp and pn cross sections and display the results in Figure 1. (For plots of other values of x_F see [4].) The lower edge of the shaded regions in the figure corresponds to $n = 4$ and the upper edge to $n = 6$. Overall the best representation of the data lies in this range. This collision number shift is easily converted to a coherence time. Let τ_0 be the coherence time in the c.m. frame of the colliding nucleons. This is essentially the same as the formation time of a pion since most pions are produced with rapidities near zero in that frame. The first proton-nucleon collision is the most important, so boosting this time into the rest frame of the target nucleus and converting it to a path length (proton moves essentially at the speed of light) gives $\gamma_{\rm cm}\, c\, \tau_0 \approx \sqrt{\gamma_{\rm lab}/2}\, c\, \tau_0$. This path length may then be equated with n times the mean free path $l = 1/\sigma_{\rm NN}^{\rm tot}\rho$. Using a total cross section of 40 mb and a nuclear matter density of 0.155 nucleons/fm^3 we obtain a path length of 8$\pm$2 fm and a proper coherence time of 0.4$\pm$0.1 fm/c corresponding to $n = 5 \pm 1$.

This value of the proper coherence time is just about what should have been expected *a priori*. In the c.m. frame of the colliding nucleons at the energies of interest a typical pion is produced with an energy of $E_\pi \approx 500$ MeV. By the uncertainty principle this takes a time of order $\hbar c/E_\pi \approx 0.4$ fm/c.

2.2. J/ψ production and absorption

A process related to Drell-Yan is the production of J/ψ which we shall address now. This is also a relatively hard process and so both energy loss of the beam proton and the Landau-Pomeranchuk-Migdal effect must be taken into account. However, there is an additional effect which plays a role, and that is the occasional absorption or breakup of the J/ψ in encounters with target nucleons. (The inelastic interaction of one of the leptons in Drell-Yan production with target nucleons is ignorably small.) The absorption cross section, $\sigma_{\rm abs}$, has been estimated in a straightforward Glauber analysis without energy loss and with an infinite coherence/formation time to be about 6-7 mb [9]. This has formed the basis for many analyses of J/ψ suppression in heavy ion collisions. Any anomalous suppression may be an indication of the formation of quark-gluon plasma [11], hence the importance of obtaining the most accurate value of $\sigma_{\rm abs}$ possible. This cross section has also been inferred from photoproduction experiments of J/ψ on nuclei from which a value much less than that has been obtained [12]. This has been a puzzle. One attempt to resolve this apparent discrepancy consists of modeling the produced J/ψ state as a pre-resonant color dipole state with two octet charges [13]; however, the results are only semi-quantitative.

In order to compute the production cross section of J/ψ in proton-nucleus collisions we need a parametrization of it in the more elementary nucleon-nucleon collisions. For this we call upon the parametrization of a compilation of data by Lourenço [14].

$$B\sigma_{NN\to J/\psi}(x_F > 0) = 37\left(1 - m_{J/\psi}/\sqrt{s}\right)^{12}\ \text{nb} \tag{1}$$

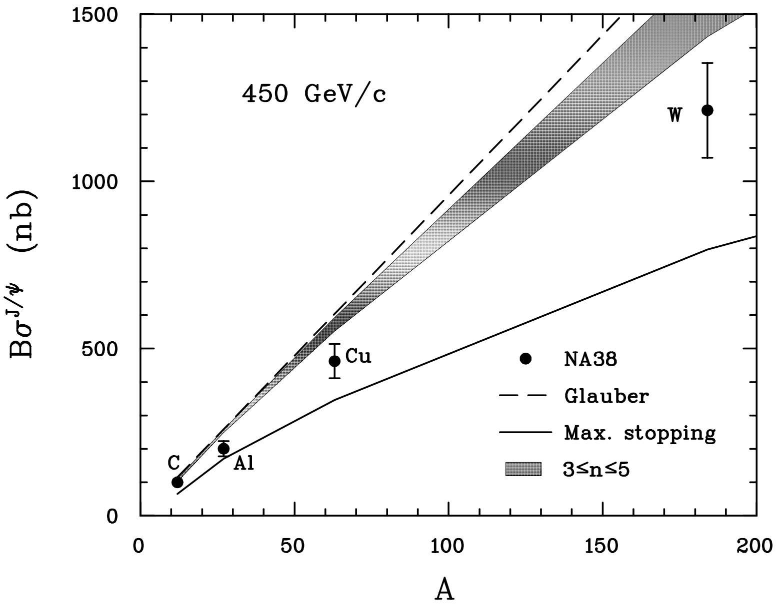

Figure 2. Branching ratio into muons times cross section to produce J/ψ with $x_F \geq 0$ in proton-nucleus collisions at 450 GeV/c. The data is from NA38 [14]. The dashed line is A times the nucleon-nucleon production cross section. The solid curve represents full energy loss with zero coherence/formation time, while the banded region represents partial energy loss with a coherence/formation time within the limits set by Drell-Yan production. (Computations were done for C, Al, Cu, W and U and the points connected by straight lines to guide the eye.)

Here B is the branching ratio into dimuons and x_F is the ratio of the momentum carried by J/ψ to the beam momentum in the center of mass frame ($-1 < x_F < 1$). Due to the degradation in momentum of the proton as it traverses the nucleus it is important to know the x_F dependence of the production. The Fermilab experiment E789 has measured this dependence at 800 GeV/c [15] to be proportional to $(1-|x_F|)^5$. Assuming that this holds at lower energy too we use the joint $\sqrt{s}$ and x_F functional dependence and magnitude:

$$\frac{d\sigma_{NN\to J/\psi}}{dx_F} = 6\sigma_{NN\to J/\psi}(x_F > 0)(1-|x_F|)^5 \,. \tag{2}$$

The cross section in proton-nucleus collisions can now be computed in LEXUS with no ambiguity.

Figure 2 shows the results of our calculation in comparison to data taken by NA38 [14]. The dashed curve is A times the nucleon-nucleon production cross section; it obviously overestimates the data. The solid curve shows the result of LEXUS with full energy degradation of the beam proton without account taken of the Landau-Pomeranchuk-Migdal effect; it obviously underestimates the data. The hatched region represents the inclusion of the latter effect with a proper formation/coherence time τ_0 in the range of 0.3 to 0.5 fm/c consistent with Drell-Yan production. The time delay is implemented as described previously: the energy available for the production of J/ψ is that which the

proton had n collisions prior; that is, the previous n collisions are ignored for the purpose of determining the proton's energy. This is an approximate treatment of the Landau-Pomeranchuk-Migdal effect. The n is related to the beam energy and to the coherence time τ_0 in the center of mass frame of the colliding nucleons. Using, as before, a total cross section of 40 mb, a nuclear matter density of 0.155 nucleons/fm^3, and $0.3 < \tau_0 < 0.5$ fm/c we obtain $2 < n < 3$ at 200 GeV/c and $3 < n < 5$ at 450 GeV/c. As may be seen from the figure, the data is overestimated, indicating the necessity for nuclear absorption.

We now introduce a J/ψ absorption cross section on nucleons and compute its effect within LEXUS in the canonical way [9,10]. When the J/ψ is created there will in general be a nonzero number of nucleons blocking its exit from the nucleus. Knowing where the J/ψ is created allows one to calculate how many nucleons lie in its path, and hence, to compute the probability that it will be dissociated into open charm. We choose a value of τ_0 allowed by Drell-Yan measurements, mentioned above, and then vary $\sigma_{\rm abs}$, assuming that it is energy independent. The lowest value of chi-squared for the 200 and 450 GeV/c data set taken together is obtained with $\tau_0 = 0.5$ fm/c and $\sigma_{\rm abs} = 3.6$ mb. The results are shown in Figure 3. The fitted values all lie within one standard

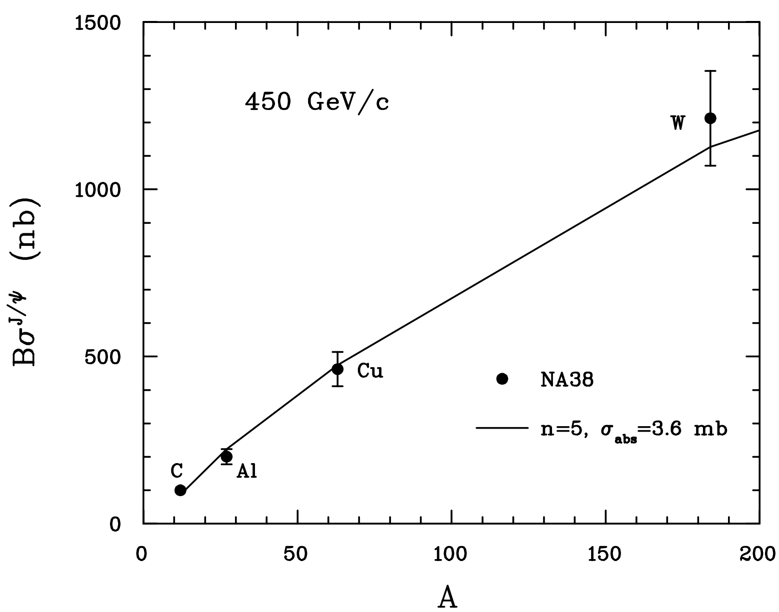

Figure 3. Same data as in Figure 2. The solid curve is the best fit of the model which includes beam energy loss with a coherence time of 0.5 fm/c (n=5 at this energy) and a J/ψ absorption cross section of 3.6 mb.

deviation of the data points. This is quite a satisfactory representation of the data. It means that both Drell-Yan and J/ψ production in high energy proton-nucleus collisions can be understood in terms of a conventional hadronic analysis when account is taken of the energy loss of the beam proton, the Landau-Pomeranchuk-Migdal effect, and nuclear absorption of the J/ψ in the final state. It also means that the absorption cross section

for J/ψ inferred from high energy proton-nucleus collisions is consistent with the value inferred from photoproduction experiments on nuclei.

3. NUCLEUS-NUCLEUS COLLISIONS

We are now ready to apply our model to nucleus-nucleus collisions. Recall that the coherence time is determined by comparing to high energy proton-nucleus Drell-Yan data, and that the J/ψ nuclear absorption is determined by comparing to proton-nucleus results. Those parameters are now kept fixed.

Table 1

	Process	$\sigma^{\rm tot}_{\rm expt.}$	n=∞	n=3	n=2
S+U:					
	Drell-Yan	$310 \pm 10 \pm 25$ nb	443	323	267
	J/ψ	$7.78 \pm 0.04 \pm 0.62$ μb	11.5	7.92	6.46
Pb+Pb:					
	Drell-Yan	$1.49\pm 0.01 \pm 0.11$ μb	2.13	1.32	1.02
	J/ψ	$21.9\pm 0.02 \pm 1.6$ μb	45.5	26.7	20.2

The S+U processes are measured by NA38 [17] in collisions at 200 GeV/c, and the Pb+Pb processes are measured by NA50 [18] in collisions at 158 GeV/c.

In the kinematical region appropriate for the CERN nucleus-nucleus experiments we find the absolute total cross-sections given in Table 1. At the energies relevant for the table, the kinematical arguments presented in section 2 tell us that we should have $2 \leq\ n \leq\ 3$. From the table, we see that the calculations satisfy this condition for the data involving the S projectile. With the heavier system, the measured J/ψ production cross section just lies in the required interval, while the Drell-Yan value is slightly underestimated. Notice in particular that the calculations with no energy loss ($n = \infty$) overshoot all the experimental values.

We can also calculate the J/ψ/Drell-Yan ratio and compare the results to NA38 and NA50 measurements. Turning first to S+U collisions at 200 GeV/c, we plot the results of the calculation together with the experimental data in Figure 4. We use the value of n suggested by minimizing χ^2 in an analysis of proton-nucleon data; see Figure 3 and Reference [10]. The impact parameter range corresponding to a given bin in transverse energy is extracted by the experimental collaboration [17]. One sees that the measurements are reproduced by the model without any new parameters. There is some room for improvement within the experimental constraints we have chosen for ourselves; however, such fine tuning is not warranted here and we will postpone this exercise [19]. Applying the model to the Pb+Pb data from NA50 [20], we get the full curve shown in Figure 5. Clearly, these experimental data are not reproduced in trend nor in magnitude. Bear in mind, however, that the quality of this fit is very comparable to other calculations with

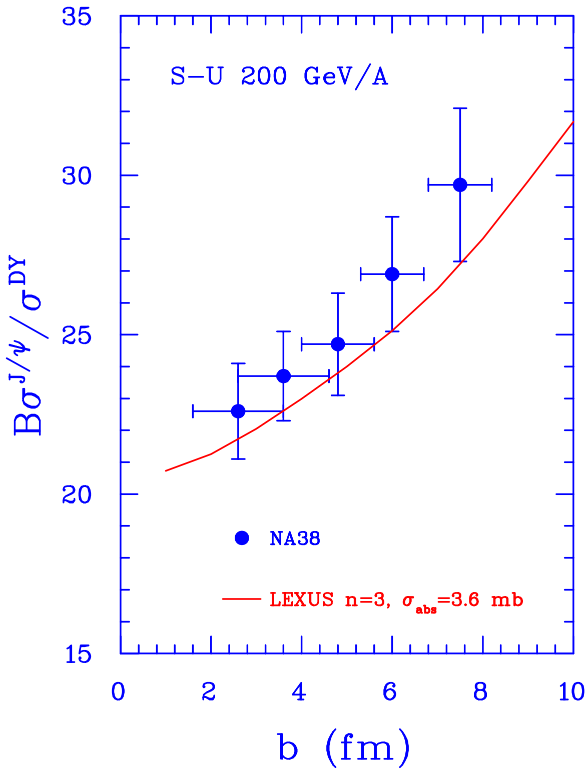

Figure 4. Ratio of J/ψ to Drell-Yan production cross sections. B is the branching ratio into a muon pair. The data is from Reference [17].

purely hadronic scenarios [21]. In Figure 5, the dashed line shows the same ratio without energy loss. The impact parameter has been extracted by the experimental collaboration.

4. CONCLUSION

The analysis performed here can and should be improved upon. What we have done is a rough approximation to adding the quantum mechanical amplitudes for a proton scattering from individual nucleons within a nucleus. A more sophisticated treatment would undoubtedly lead to even better agreement with experiment, but the inferred value of the proper coherence time is unlikely to be much different than obtained with this first estimate. It will be very instructive to repeat this analysis in the language of partonic variables. Actually, the analysis with parton energy loss alone was reported by Gavin and Milana [22] with satisfactory results obtained for Drell-Yan if the quarks/antiquarks lose about 1.5 GeV/fm. Nuclear shadowing [23] needs to be taken into account too. The relationship among all these effects is not well-understood, nor is the relationship between these effects in partonic and hadronic variables.

Our calculation of the J/ψ-to-Drell-Yan ratio is in agreement with the data for the light system, but fails with the Pb+Pb system. A systematic exploration of the freedom allowed by present parametrizations of the nucleon-nucleon experimental data is called

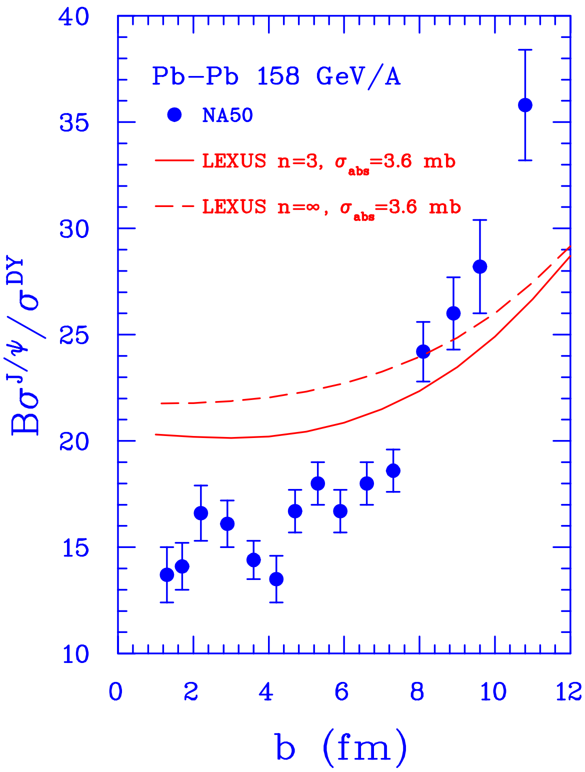

Figure 5. Ratio of J/ψ to Drell-Yan production cross sections. B is the branching ratio into a muon pair. The data is from Reference [20].

for [19]. It may be that after a more thorough treatment, the need for a picture with J/ψ absorption on "co-movers" [9,24] will emerge here also. This, and the issues enumerated above are being investigated.

5. ACKNOWLEDGEMENTS

This work was supported by the U. S. Department of Energy under grant DE-FG02-87ER40328, by the Natural Sciences and Engineering Research Council of Canada, by the Fonds FCAR of the Quebec Government, by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of Nuclear Physics, and by the Office of Basic Energy Sciences, Division of Nuclear Sciences, of the U.S. Department of Energy under contract No. DE-AC03-76SF00098.

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